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Spatial distribution and temporal trends in precipitation extremes over the Hengduan Mountains region, China, from 1961 to 2012

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ABSTRACT

Extreme precipitation events will cause serious disasters, and their changing trends require thorough evaluation. Spatial distribution and temporal trends of extreme precipitation events were analyzed based on the daily precipitation data of 27 meteorological stations in the Hengduan Mountains region from 1961 to 2012. Twelve indices of precipitation extreme were studied. The results were as follows: except for consecutive dry days, consecutive wet days and maximum 5-day precipitation, other indices of precipitation extreme demonstrated non- significant increasing trends, and most indices fluctuated from 1961 to 2012. Increasing trends in precipitation indices were greater than those in precipitation days. The spatial distribution for precipitation extremes exhibited a declining trend from southwest to northeast, which reflected regional differences and the influence of topography in the Hengduan Mountains region. Furthermore, the relationship between precipitation extremes and elevation indicated that precipitation extreme events decreased with altitude. The extreme precipitation indexes had positive correlations with the annual total precipitation, and their correlation coefficients were statistically significant at the 1% significance level, except for consecutive dry days. Continuous wavelet transform analysis presented significant periodic variations with periods of 2–4 year, 5-year, and 10-year in the extreme precipitation, and there was a 2–4 year resonance cycle with the South/East Asian summer monsoon index. The South/East Asian Summer Monsoon was an important influence on precipitation extremes in the Hengduan Mountains region.

1. Introduction

The subject of climate changes has become increasingly important, because of the numerous extreme weather events, such as droughts and floods (Boccolari and Malmusi, 2013). It is well known that the frequency and intensity of extreme weather and climatic change might have greater influence on nature and human society than changes in the average value (Kunkel et al., 1999; New et al., 2006; Katz and Brown, 1992; Aguilar et al., 2008; Liu et al., 2009; You et al., 2010). Extreme precipitation events in climate change seem to be occurring more frequently worldwide (MunichRe, 2002; Kunkel, 2003; Beniston and Stephenson, 2004; Christensen and Christensen, 2004; Zhang et al., 2008, 2009; Zolina et al., 2010). Therefore, the increase in extreme weather events caused by the global climatic change has attracted great attention, especially in meteorological circles (Frich et al., 2002; Zhai and Pan, 2003; Goswami et al., 2006; IPCC, 2007; Zhang et al., 2012; Guo et al., 2013).

Due to the increased water vapor in the atmosphere, the increase of temperature is considered to be related with the recent increase in extreme precipitation events (Zhang et al., 2012). Consequently, extensive studies of extreme precipitation events have been carried out in many regions around the world (Kunkel, 2003; Kunkel et al, 2003; Zhai et al., 2005; New et al., 2006; Endo et al., 2009; Durao et al., 2010; Ren et al., 2010; Caesar et al., 2011; You et al., 2011), aiming to understand their mechanisms and to find adaptive measures. In China, the changing trends in extreme precipitation events are basically consistent with those globally. The frequency, scale and duration of extreme precipitation events are growing and present obvious regional characteristics (Zhai and Pan, 2003, 2005; Ren et al., 2010; You et al., 2011; Li et al., 2012a; Guo et al., 2013; Wang et al., 2013a,b,c). Furthermore, several studies suggested that increased and decreased precipitation extreme events also showed spatial variations (Zhang et al., 2012; Li et al., 2012a; Guo et al., 2013; Wang et al., 2013a,b,c). Generally, characteristics of extreme precipitation

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have been studied at large spatial scales, but changes in particular regions have not been conclusive (Su et al., 2008). Regional assessment in different climate and geographical regions are needed to understand the uncertainties of changing trends in extreme weather events (Nie et al., 2012). Moreover, regionalization can also provide a basis for local planning and countermeasures to adapt to climate change. Located at the junction of the first and second step of China, the Hengduan Mountains region (HDMR) affects the climate and ecological environment of its surrounding areas, and even central and western China (Zhu et al., 2011). It is also an obstruction to the eastern Asia monsoon and a thoroughfare to the southern Asia monsoon (Li et al., 2011; Zhu et al., 2011). The strength or weakness of the monsoon often leads to extreme rainfall events. However, precipitation extremes in the HDMR separated from southwest China have never been analyzed in detail. The primary goal of this study is to identify the variations in frequency, intensity, and duration of precipitation extremes over the HDMR from 1961 to 2012. We also investigated the relationships between elevation and precipitation extremes at all stations. It is hoped that this study will provide valuable information to policymakers and researchers and play an important role in assessing and predicting the influence of extreme weather events influencing floods and droughts in the HDMR.

2. Data and methods

2.1. Study area

Hengduan Mountains region (HDMR), with an area of 500,000 km^2 (Fig. 1), lies in the southeastern part of Qinghai-Tibet Plateau (24°40′-34°00′N; 96°20′-104°30′E). It covers Changdou city, Tibetan Autonomous Region, Ganzi, Aba, and Liangshan cities, Sichuan province, and Deqing, Dali, Nujiang and Lijiang cities, Yunnan province (Li and Su, 1996; Li et al., 2011; Zhu et al., 2011). There are a series of mountain ranges and rivers, including Mt. Minshan, Mt. Shalulishan, Mt. Habaxueshan, Mt. Yulong, Mt. Ningjingshan, Mt. Daxueshan, Mt. Qionglaishan, Nujiang River, Daduhe River, Mijing River, Jinshajiang River, Yalongjiang River, and Lancangjiang River. The mountains' altitude is above 5000 m in the north and above 4000 m in the south (Li and Su, 1996). All rivers in this area drain into the Pacific Ocean except the Nujiang River, which is a part of the Indian Ocean water-system (Li et al., 2011). Due to the effect of cutting of the higher mountains and rivers, the HDMR is a world-famous longitudinal range-gorge area (Gao and Zheng, 1989). The topography declines from northwest to southeast. Located in the plateau temperate subtropical and climate zones, the climate differs sharply due to the complex mountainous topography (Li et al., 2011; Zhu et al., 2011). Owing to the topography, the abundant precipitation in the accumulation area and the low temperature in the higher altitude area, the HDMR is the southernmost and easternmost glacial area in China (Li et al., 2011). The precipitation was more plentiful in glacier areas of the HDMR (Xin et al., 2012). The HDMR is also a typical monsoon climate zone, which is controlled by the South Asia monsoon as well as the East Asia monsoon (Li and Su, 1996).

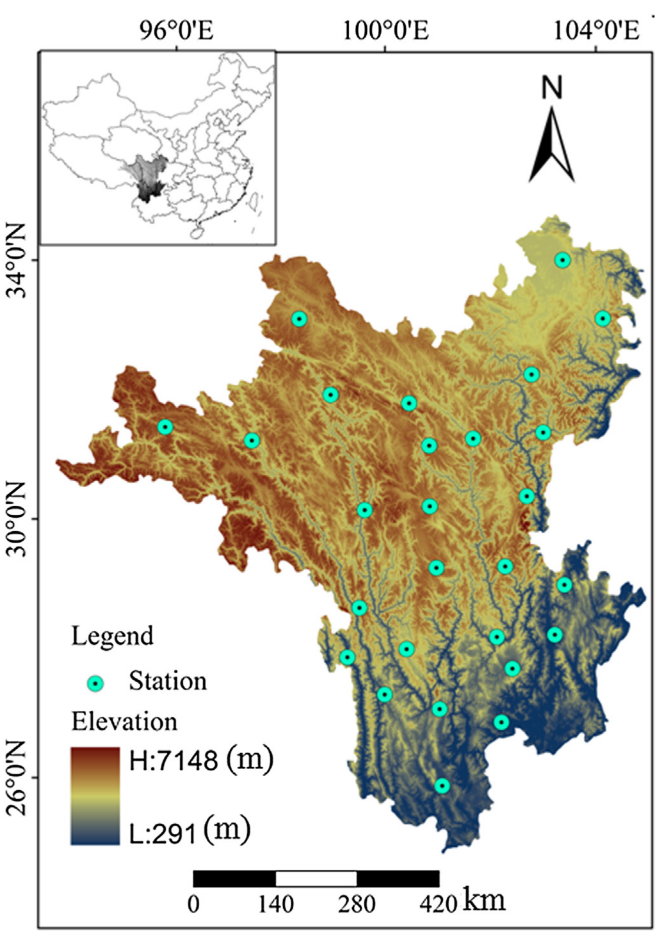

Fig. 1. The DEM and location of meteorological stations in the HDMR.

2.2. Data

The daily precipitation observational data from 1961 to 2012 are provided by the National Meteorological Information Center of China Meteorological Administration (available at http://www nmic.gov.cn/). According to the standards whereby observed data are continuous and data series are as long as possible, 27 meteorological stations in the HDMR were selected (Fig. 1). Detailed information including the WMO number, latitude, longitude, and altitude is shown in Table 1. The altitude of these selected stations ranges from 1244 m (Huaping) to 4200 m (Shiqu).

Table 1
List of observation stations with WMO number, latitude, longitude, altitude in the study area.

WMO number	Station name	Latitude(N)	Longitude(E)	Altitude(m)
56664	Huaping	26°38′	101°16′	1244.8
56533	Gongshan	27°45′	98°40′	1583.3
56571	Xichang	27°54′	102°16′	1590.9
56475	Yuexi	28°39′	102°31′	1659.5
56751	Dali	25°42′	100°11′	1990.5
56548	Weixi	27°10′	99°17′	2326.1
56178	Xiaojin	31°00′	102°21′	2369.2
56651	Lijiang	26°52′	100°13′	2392.4
56459	Muli	27°56′	101°16′	2426.5
56565	Yanyuan	27°26′	101°31′	2545
56247	Batang	30°00′	99°06′	2589.2
56374	Kangding	30°03′	101°58′	2615.7
56172	Maerkang	31°54′	102°14′	2664.4
56182	Songpan	32°39′	103°34′	2850.7
56167	Daofu	30°59′	101°07′	2957.2
56462	Jiulong	29°00′	101°30′	2987.3
56251	Xinlong	30°56′	100°19′	3000
56144	Dege	31°48′	98°35′	3184
56543	Zhongdian	27°50′	99°42′	3276.7
56137	Changdu	31°09′	97°10′	3306
56444	Deqin	28°29′	98°55′	3319
56146	Ganzi	31°37′	100°00′	3393.5
56079	Ruoergai	33°35′	102°58′	3439.6
56357	Daocheng	29°03′	100°18′	3727.7
56116	Dingqing	31°25′	95°36′	3873.1
56257	Litang	30°00′	100°16′	3948.9
56038	Shiqu	32°59′	98°06′	4200

Data quality control is a precondition in climate change research. A simple quality control is operated using RClimDex software (software and documentation available for download from http://cccma.seos.uvic.ca/ETCCDMI), developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch, Meteorological Service of Canada. The RClimDex can calculate precipitation extremes indices on the basis of daily precipitation amount. After data quality control and homogeneity, twelve precipitation indices (Table 2) were selected. These indices are widely used to evaluate the changes in precipitation extremes (Frich et al., 2002; New et al., 2006; Choi et al., 2009; Vincent et al., 2011; Li et al., 2012a; Wang et al., 2013a,b,c). The South Asian summer monsoon index (SASMI) and East Asian Summer Monsoon Index (EASMI) were used to represent large-scale climate anomalies with data from http://ljp.lasg.ac.cn/dct/page/.

Table 2
Definitions of precipitation indices used in this study.

Index	Descriptive name	Definition	Units
NW	Wet days	Annual count of days when RR ≥ 1 mm	Days
CDD	Consecutive dry days	Maximum number of consecutive dry days	Days
CWD	Consecutive wet days	Maximum number of consecutive wet days	Days
R10 mm	Heavy precipitation days	Annual count of days when RR ≥ 10	Days
R20 mm	Heavier precipitation days	Annual count of days when RR ≥ 20	Days
R25 mm	Heaviest precipitation days	Annual count of days when RR ≥ 25	Days
SDII	Simple daily intensity index	Average precipitation on wet days	mm/day
PRCPTOT	Wet day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm
RX1day	Maximum 1-day precipitation	Annual maximum 1-day precipitation	mm
RX5day	Maximum 5-day precipitation	Annual maximum consecutive 5-day precipitation	mm
R95	Very wet day precipitation	Annual total precipitation when RR > 95th percentile of 1981–2010 daily rainfall	mm
R99	Extremely wet day precipitation	Annual total precipitation when RR > 99th percentile of 1981–2010 daily rainfall	mm

Notes: All indices are calculated from January to December. Abbreviations are as follows: RR daily precipitation; A wet day is defined when RR ≥ 1 mm and a dry day when RR°<°1 mm.

2.3. Methods

Precipitation extremes can be calculated in various ways, for example, the set of twelve indices of extremes within the STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions), which can reflect the change of extreme climate in different aspects with relatively weak extremes, low noise and strong significance (Frich, 1999). These extreme indices can be divided into two types (Wang et al., 2013a,b,c). One is precipitation index (simple daily intensity index, wet day precipitation, maximum 1-day precipitation, maximum 5-day precipitation, very wet day precipitation, extremely wet day precipitation), and the other is the precipitation days (Wet days, consecutive dry days, consecutive wet days, heavy precipitation days, heavier precipitation days, heaviest precipitation days).

Changes in precipitation extremes were analyzed at a temporal and spatial scale based on the software of OriginPro, SPSS (Statistical Product and Service Solutions), ArcGIS and Matlab. The FFT filtering and the linear regression were used to show annual trends, which are widely employed in extreme climate research. This trend is considered to be statistically significant if it is significant at the 5% significance level using a two-tailed *t*-test (Rahimzadeh et al., 2009; Wang et al., 2013a,b,c). The index of the regional annual series was calculated as the arithmetic mean at 27 stations over the HDMR. Furthermore, the periodic characteristics were analyzed by the continuous wavelet transform (CWT). Wavelet analysis is used to reveal the periodic characteristics of climate change and test periodic variation in different time scales (Weng and Lau, 1994; Ling et al., 2012; Wang et al., 2013a,b,c). To quantify changes in large scale atmospheric circulation, the South Asian Summer Monsoon Index (SASMI) and East Asian Summer Monsoon Index (EASMI) were used to analyze their relationships with precipitation extremes. Cross wavelet transform (XWT) was used to analyze the correlation relationship between main climate factors (SASMI, EASMI) and extreme precipitation (Grinsted et al., 2004).

3. Results

3.1. Temporal trends of precipitation extremes indices

3.1.1. Temporal trends of precipitation index

The regional average value of precipitation extremes relative to the 1981–2010 mean value in the HDMR are shown in Fig. 2a–f and Table 3. In addition to maximum 5-day precipitation (RX5day), other indices demonstrated an increasing trend, and most indices fluctuated increasingly from 1961 to 2012. However, all the linear trends for each index were not statistically significant. As for the maximum 1-day precipitation (RX1day), approximately 63% of the stations had increasing trends. The stations where RX5day exhibited decreasing trends accounted for 63%. The RX5day showed slight decreasing trends at the rate of 1.2°mm/decade, while there was an increasing tendency for RX1day. Considering very wet day precipitation (R95), 74% of stations showed increasing trends with fluctuations, but only 4% of stations were statistically significant. For extremely wet day precipitation (R99), 56% and 44% of the stations showed respectively a positive and a negative trend. The regional trends of R95 and R99 were 4.21 and 1.5°mm/decade from 1961 to 2012, respectively (Fig. 2e and f). The wet day precipitation (PRCPTOT) had increased at a rate of 5.05°mm/decade, whereas the average precipitation on wet days (SDII) had increased by 0.06 mm/d/decade and 14% of stations did not present any significant trend over the 1961 to 2012 period.

Table 3
Percentage of stations with positive (significant at the 0.05 level), non-trend, and negative (significant at the 0.05 level) trends for the precipitation indices from 1961 to 2012.

Index	Trend	Positive	Non-trend	Negative
NW	I	63%(18%)	0	37%(7%)
CDD	D	33%	0	67%(7%)
CWD	D	33%	0	67%(14%)
R10 mm	I	59%	0	41%
R20 mm	I	52%	7%	41%
R25 mm	I	56%(4%)	11%	33%
RX1day	I	63%(4%)	0	33%
RX5day	D	37%	0	63%
PRCPTOT	I	67%(4%)	0	33%
SDII	I	56%	14%	30%(4%)
R95	I	74%(4%)	0	26%
R99	I	56%	0	44%

Note: D, indicates that the regional trends is decreased and I, indicates that the regional trends in is increased in the HDMR.

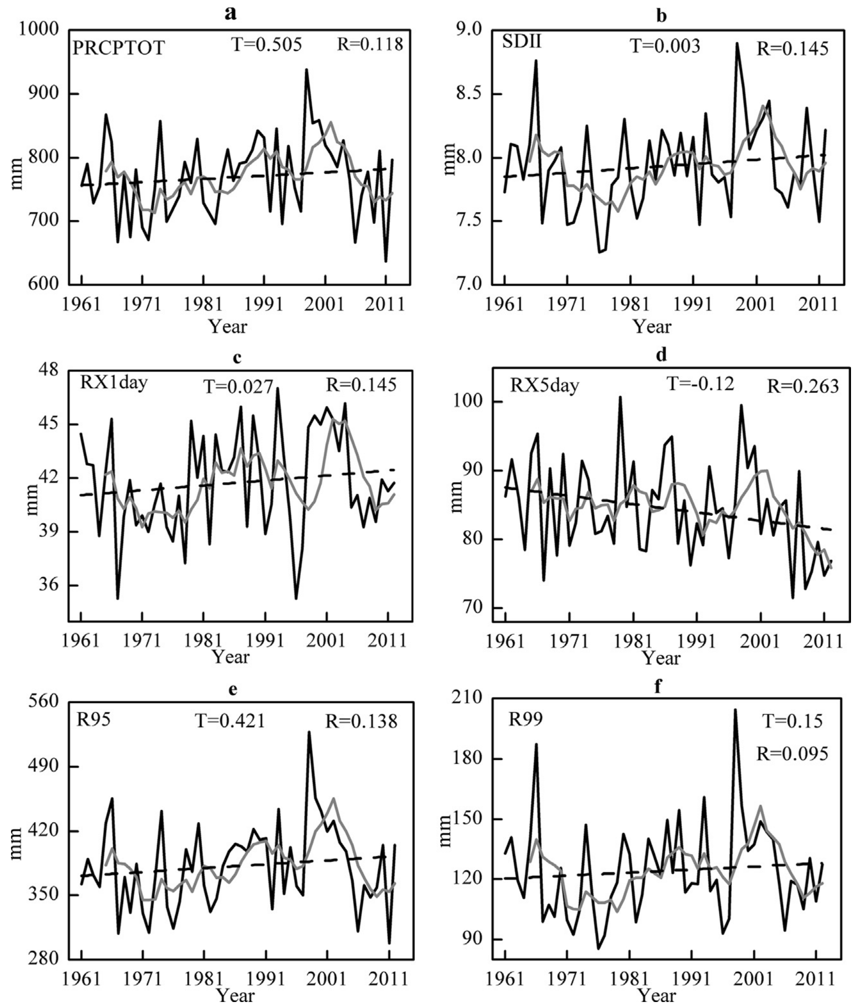

Fig. 2. Inter-annual variation of precipitation indices in the HDMR from 1961 to 2012. The dashed line is the linear trend; The grey line is the five-year smoothing average. T and R are its change trend and correlation coefficient.

3.1.2. Temporal trends of precipitation days

In a majority of cases, most precipitation indices suggested that the amount and intensity of rainfall are increasing. During the research period, the indices of the precipitation days demonstrated increasing trends (Fig. 3a–f and Table 3), except consecutive dry days (CDD) and consecutive wet days (CWD). Similarly, all the linear trends for each index were not statistically significant. The CDD had a slightly decreasing trend at a rate of 0.56 d/decade from 1961 to 2012. The decreasing trend for CDD was more significant than that for CWD. The CWD of stations had decreasing trends by 0.12 d/decade, and 14% out of 67% decreasing stations showed significant trends in the data series at the 5% significance level. The regionally averaged occurrence of heavy precipitation days (R10 mm), heavier precipitation days (R20 mm) and heaviest precipitation days (R25 mm) had an increasing trend, nonetheless, they were not statistically significant. The increase rates in R10 mm, R20 mm and R25 mm were 0.15, 0.45and 0.09 day/decade, respectively. The proportions of stations with positive trends for R10 mm, R20 mm and R25 mm were 59%, 56%, and 52%. For wet days (NW), the percentages of stations with positive trends and stations with negative trends were 63% (18% statistically significant) and 37% (7% statistically significant), respectively (Table 3).

3.2. Spatial distributions of precipitation extremes indices

3.2.1. Spatial distributions of precipitation index

To explore the spatial distribution of trends on precipitation extremes over the HDMR, the linear regression slope was interpolated based on each station's slope value for the entire study period (1961–2012). It provides more detailed information of how the magnitudes of rates vary in precipitation extremes among the 27 weather stations. Fig. 4 shows the spatial distribution of precipitation indices. The spatial distributions for precipitation extremes exhibited a declining trend from southwest to northeast over the study region. The stations with increasing trends for PRCPTOT were mainly distributed in central- northern HDMR, and the Kangding station in this district was statistically significant at the 5% significance level. The increase of SDII was mainly in the central-southern HDMR and the decrease was centralized in northern HDMR. Only Shiqu station in this district was significant at the 5% significance level. The spatial change trends for RX1day were similar to RX5day, namely, decreasing and increasing regions of RX1day and RX5day were distributed sporadically in the study area. As for R95, the stations showing decreasing trends were centered in northern and southern HDMR, but the increasing regions were scattered fragmentarily in the central-southern HDMR.

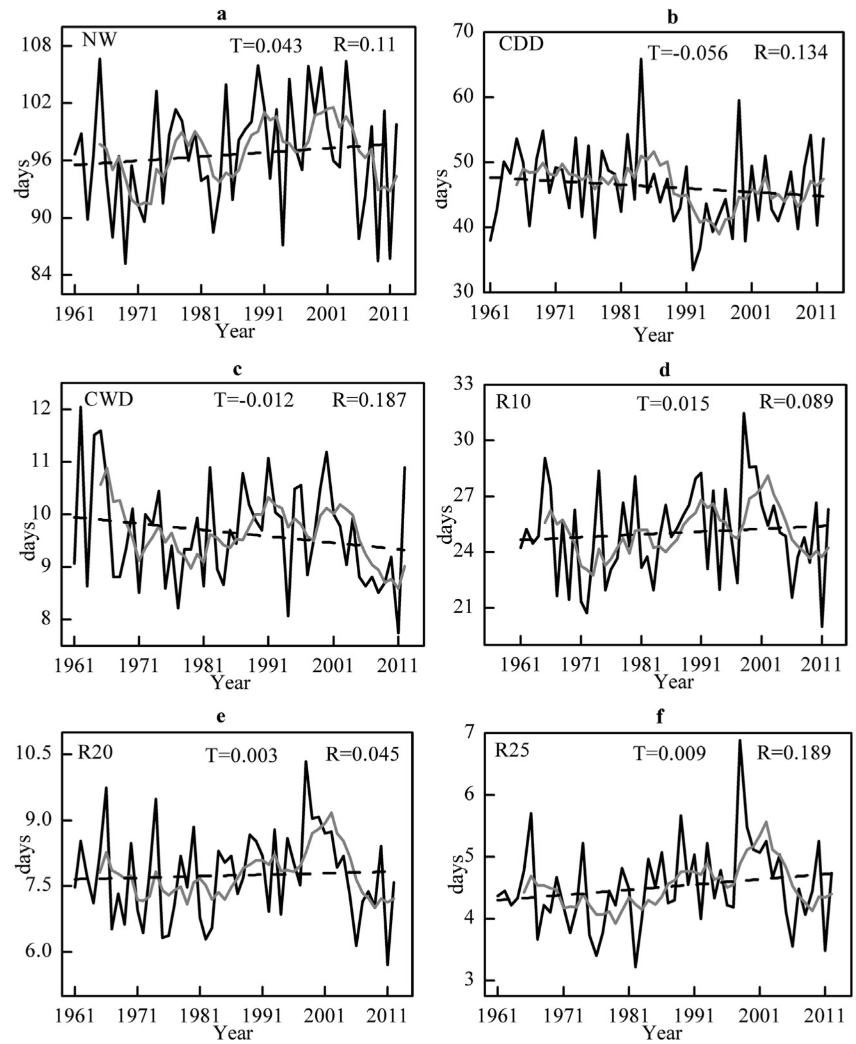

Fig. 3. Inter-annual variation of precipitation days in the HDMR from 1961 to 2012. The dashed line is the linear trend; The grey line is the five-year smoothing average. T and R are its change trend and correlation coefficient.

For R99, the stations experiencing increases were centralized in southern and stations undergoing decreases were primarily distributed in central- northern HDMR.

3.2.2. Spatial distributions of precipitation days

The spatial distributions of the change trends for the number days of precipitation are extremely different. Fig. 5 presents the spatial distribution of precipitation days from 1961 to 2012. The stations with increasing trends for NW were mainly distributed in central- northern HDMR, and Xinlong, Litang and Xiaojin stations showed statistical significance at the 5% level. Stations with decreasing trends for NW were centered in the southern district. The Lijiang and Muli stations in this region showed significant trends at the 5% significance level. The spatial distribution for CDD exhibited a declining trend from southwest to northeast over the study region. Stations experiencing a decreasing trend for CWD were centralized in the southern HDMR, and stations undergoing increases were distributed in the central and northern regions. However, Weixi, Lijiang, and Yanyuan in the southern region and Ruoergai in the northern region had statistically significant trends at the 5% significance level. The spatial change of the R10 mm, R20 mm, and R25 mm had increasing trends in most regions. The spatial distribution for R10 mm exhibited an increasing trend from south to north over the study region. More than half of the stations presented an increasing trend for R20 mm, and the trends weakened from north to south in the HDMR. For R25 mm, the regions with the largest increases were in the central HDMR, and Kangding station showed statistical significance at the 5% significance level. However, the stations in the north district had decreasing trends for R25 mm.

3.3. Relationship between the precipitation extremes and elevation

There were negative correlations between elevation and the magnitude of the trends of CDD, R20 mm, R25 mm, SDII, RX1day, R95 and R99 (Fig. 6) in the HDMR from 1961 to 2012. With increasing elevation, CDD, R20 mm, R25 mm and SDII exhibited decreasing trends statistically significant at the 5% significance level, which showed the decrease of precipitation days mainly occurred in lower altitudes over the HDMR. The regional trend of RX1day, R95 and R99 displayed a statistically negative correlation with elevation, indicating that extreme precipitation events occurred mainly at lower altitudes. However, the correlations between elevation and the trend of NW, CWD, R10 mm, RX5day, and

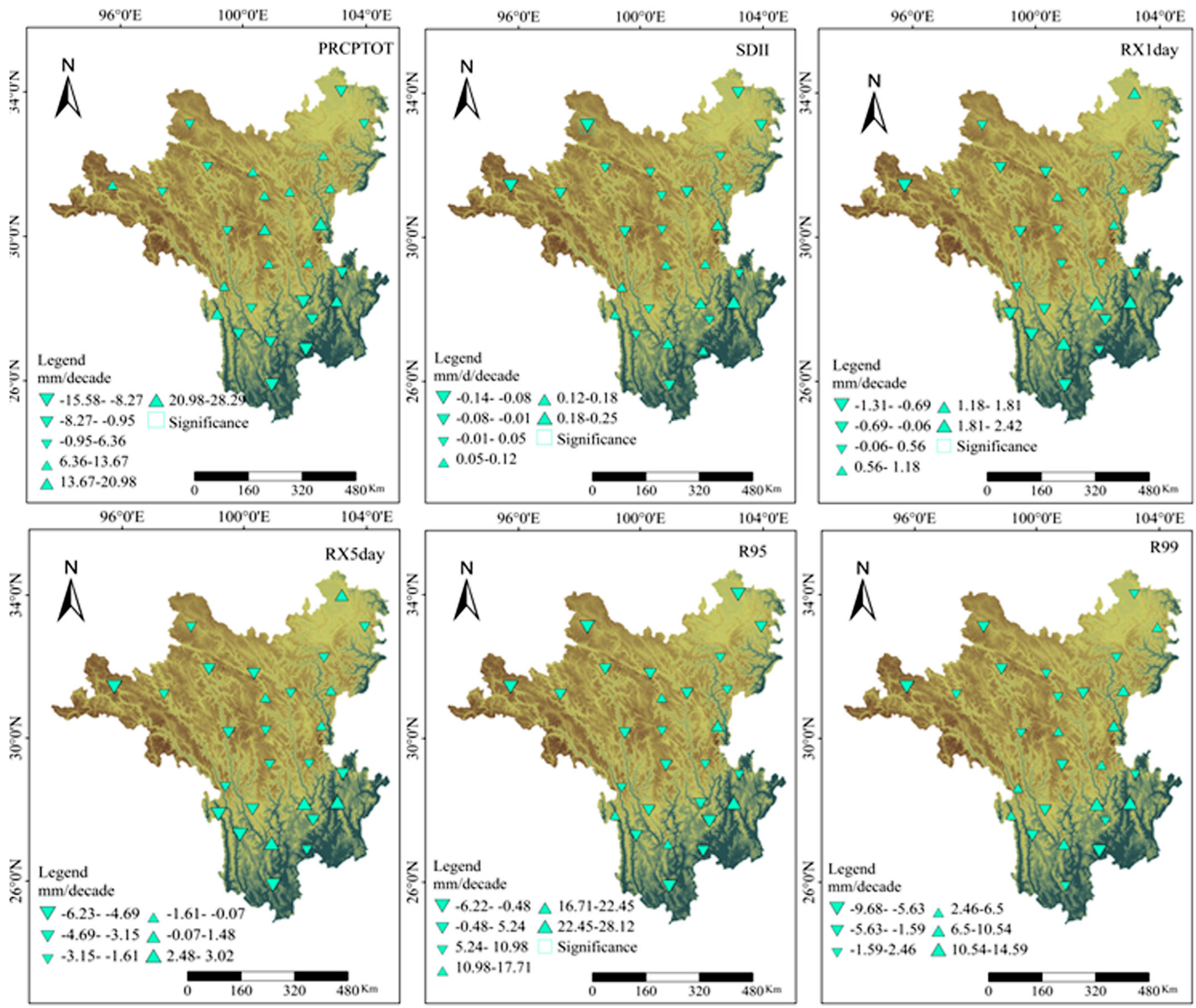

Fig. 4. Spatial distributions of precipitation index in the HDMR from 1961 to 2012.

PRCPTOT showed increasing trends with increasing altitude, especially for NW and CWD. Precipitation increases with altitude, and the rise of precipitation mainly happened in higher altitude areas. These results also reflect the complexity of regional precipitation.

3.4. *Period analysis and relationship with South/East Asian summer monsoon*

In order to learn more about the changes of precipitation extremes, it is necessary to analyze periodic features of precipitation extremes by using the continuous wavelet transform (CWT). Fig. 7 shows the continuous wavelet power spectra for the time series of R95 and R99 over the HDMR. The significant wavelet power spectra of R95 (Fig. 7a) are 2–4 year, 5-year, and 10-year modulation of variation, which existed during 1961– 1985 and 1988 to 2000, respectively. For R99 (Fig. 7b), the power is broadly distributed, with peaks in 2–4years. The 5% significant level regions indicate intervals of higher variance from1970 to 2000 with a cycle of 2–4 years. They also have 6–10 year cycles approximately, but low significance at the 5% level. There are common features in the wavelet power of the two time series, such as 2–4years and 10 years.

The HDMR is a typical monsoon climate zone, which is controlled by the South Asia monsoon as well as the East Asia monsoon. Here, the mechanism of the cross wavelet transform for the South/East Asian Summer Monsoon Index (SASMI/EASMI) and R95/R99 is considered. The cross-wavelet transform between SASMI and R95 (Fig. 8) shows that a significant power in the 2 year period during 1965–1970 as well as 1990–1996, considering that SASMI is one driver factor of precipitation variation in the HDMR. The cross-wavelet transform between SASMI and R99 shows a significant common power in the 2-year and 4–6 year band during the 1965–1975 and 1990–2000 periods. The cross-wavelet transform relationship between R95 and the East Asian Summer Monsoon Index (EASMI) shows significant shared power, although there is a small area during the 1992–2000 period with 2–4 year periodicity. The R99 and EASMI also show 2–4 year periodicity from 1992 to 2000 (Fig. 8).

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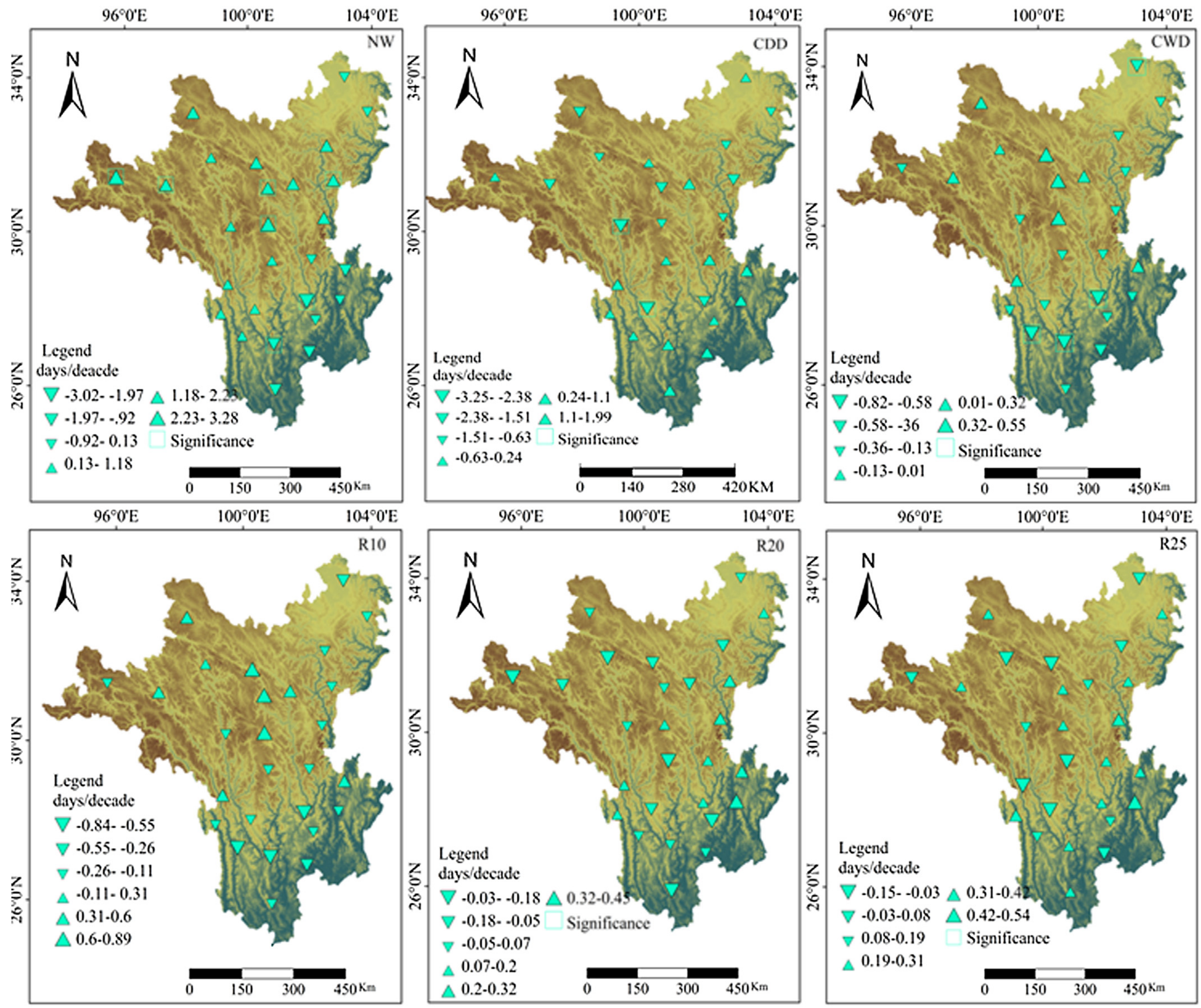

Fig. 5. Spatial distributions of precipitation days in the HDMR from 1961 to 2012.

3.5. Precipitation extremes correlated with annual total precipitation

In order to verify whether the extreme precipitation indices have a relationship with the change of annual total precipitation, the correlation coefficients between annual total precipitation and extreme precipitation indices were calculated (Table 4). In addition to CDD, the other extreme precipitation indexes have positive correlations with the annual total precipitation and their correlation coefficients are statistically significant at the 1% significance level. The correlation coefficients between total precipitation and precipitation indices, including PRCPTOT, R10 mm, R20 mm, and R95, exceeded 0.9, and the others exceeded 0.46, which indicated that the annual total precipitation is correlated with extreme precipitation. Furthermore, Table 4 also shows statistically significant correlations among the precipitation indices.

Table 4
Correlation coefficients between annual total precipitation and selected extreme precipitation indices.

	ATP	CCD	CWD	R10	R20	R25	RX5day	RX1day	SDII	PRCPTOT	R95	R99	NW
ATP	1												
CCD	0.04	1											
CWD	0.55**	0.11	1										
R10	0.97**	0.11	0.55**	1									
R20	0.91**	0.06	0.47**	0.89**	1								
R25	0.82**	0.07	0.32*	0.79**	0.90**	1							
RX5day	0.52**	0.01	0.28*	0.46**	0.55**	0.53**	1						
RX1day	0.46**	−0.08	0.09	0.36**	0.45**	0.56**	0.50**	1					
SDII	0.67**	0.23	0.34*	0.71**	0.77**	0.84**	0.46**	0.53**	1				
PRCPTOT	1.00**	0.04	0.55**	0.97**	0.91**	0.82**	0.52**	0.46**	0.68**	1			

(*continued on next page*)

Table 4 (*continued*)

	ATP	CCD	CWD	R10	R20	R25	RX5day	RX1day	SDII	PRCPTOT	R95	R99	NW
R95	0.94**	0.08	0.47**	0.93**	0.94**	0.92**	0.58**	0.56**	0.84**	0.94**	1		
R99	0.76**	−0.01	0.32*	0.71**	0.78**	0.86**	0.6**	0.71**	0.83**	0.76**	0.86**	1	
NW	0.87**	−0.10	0.53**	0.81**	0.67**	0.52**	0.34*	0.26	0.25	0.87**	0.68**	0.45**	1

Note: ATP stands for annual total precipitation. ** significant at the 1% significance level; * significant at the 5% significance level.

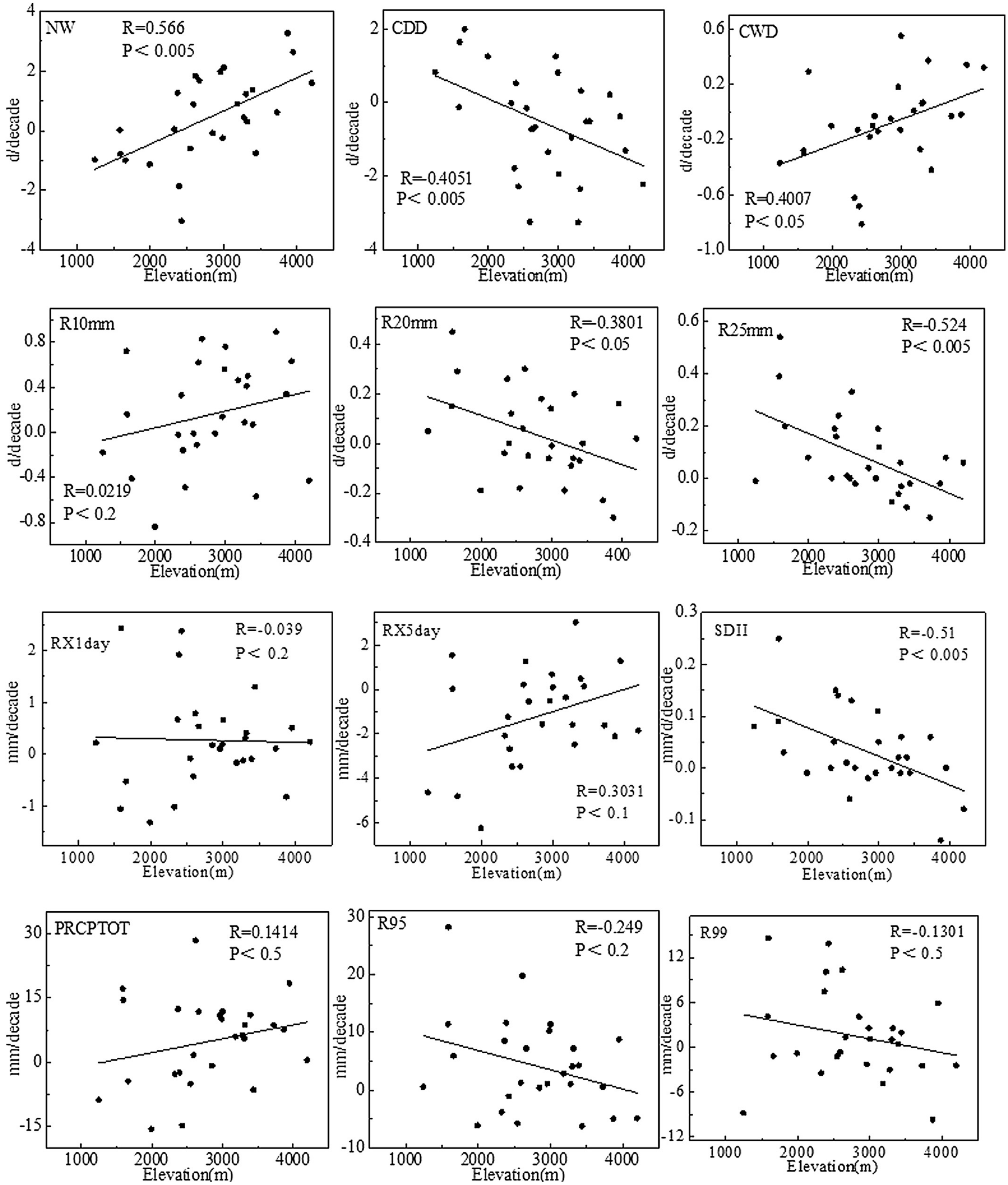

Fig. 6. Correlation between the extreme precipitation indices and elevation. (The solid line is the linear trend. R stands for correlation coefficients for the relationships and P for statistical significance.)

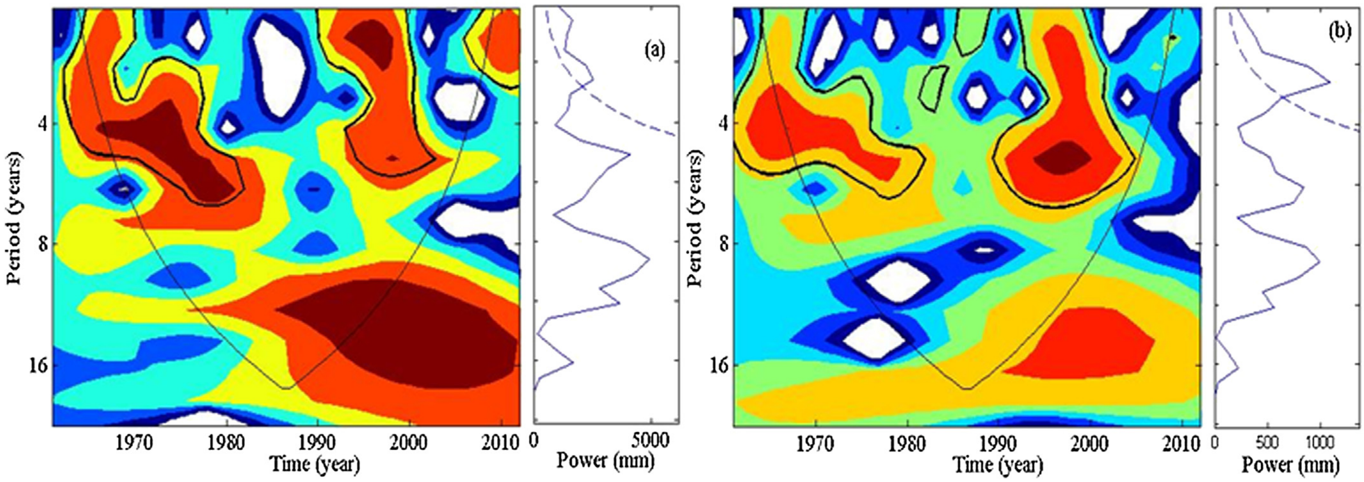

Fig. 7. Continuous wavelet power spectrum of (a) time series of average R95 and (b) R99 in the HDMR. The thick black contour designates the 5% significance level against red noise and the cone of influence (COI) where edge effects might distort is shown as the U-shaped line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

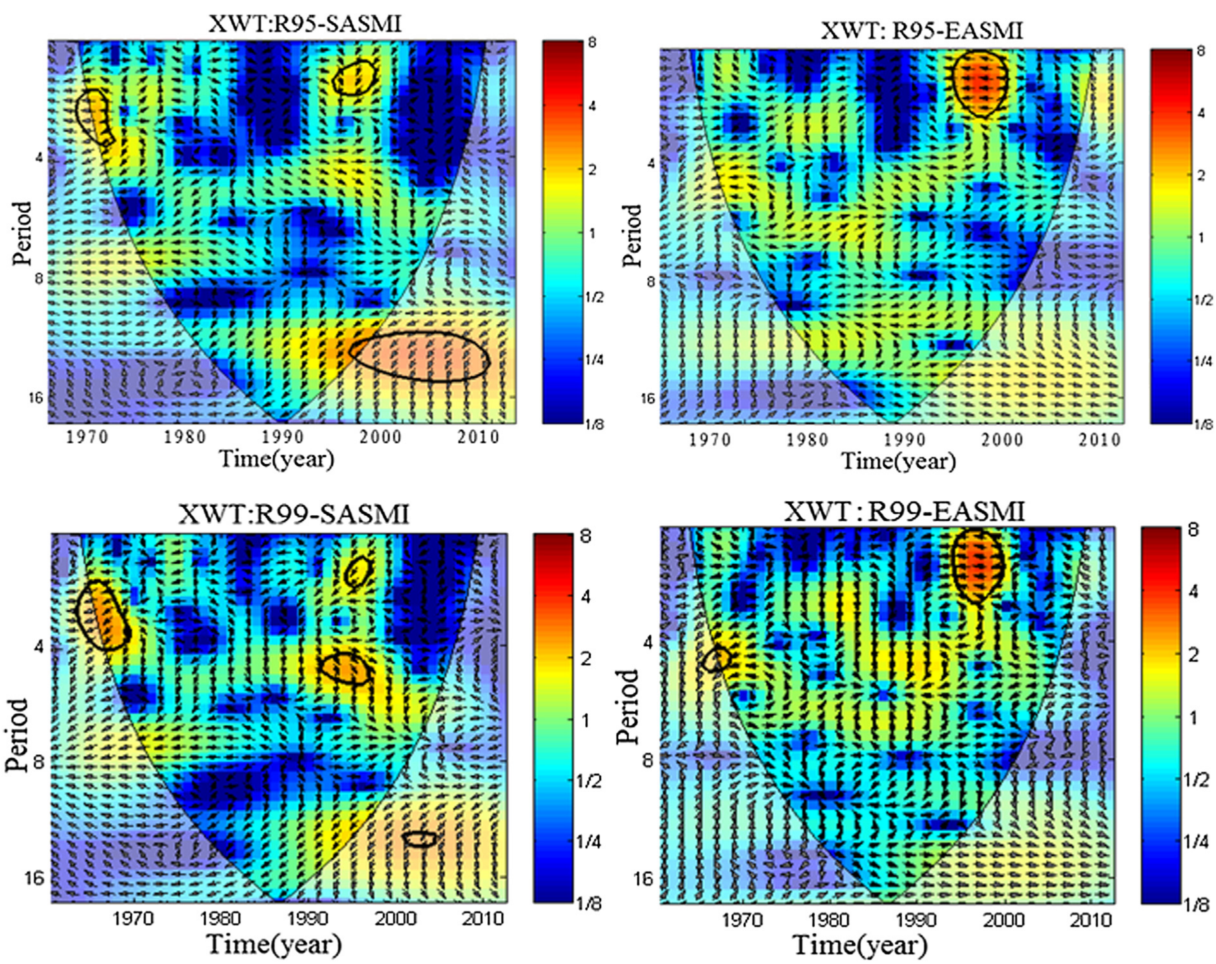

Fig. 8. Cross wavelet transform of R95 and R99 and SASMI and EASMI. The thick black contours depict the 5% significance level of local power relative to red noise, and the black line is the cone of influence. Right-pointing arrows indicate that the two signals are in phase while left-pointing arrows are for anti-phase signals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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4. Discussion

The duration, amount, and intensity of the response to climate change presented distinct geographic differences, caused by regional characteristics, climate drivers, and other factors (Li et al., 2011). Based on the results above, the general variation tendency for precipitation over the HDMR had an increasing trend, whereas CDD showed a decreasing trend. These changes differ from previous studies in other parts of China (You et al., 2011; Nie et al., 2012; Li et al., 2012a; Wang et al., 2013a,b,c) and also reflected regional changes of precipitation extremes. HDMR is a typical longitudinal mountains area, with differences from east to west and north to south (You et al., 2005; Zhu et al., 2013). Under the influence of topography, rainfall distributions had not only lateral differences but also obvious variations with altitude (Gao and Zheng, 1989; Li et al., 2012a). The precipitation in mountain areas increased along with altitude, but decreased after growing to a certain height (Li and Su, 1996; Zhu et al., 2013). The regional trend of precipitation extremes displayed a statistically negative correlation with elevation in the HDMR, indicating that extreme precipitation events occurred mainly at lower altitudes. However, the correlations between elevation and the trend of NW, CWD, and R10 mm showed increasing trends with increasing altitude. In addition, the HDMR was the southernmost and easternmost glacial area in China because of the abundant precipitation in the higher altitude area (Li et al., 2011; Zhu et al., 2013) and the precipitation was more plentiful in glacier areas of the HDMR (Xin et al., 2012). In the eastern slope of Yulong Snow Mountain, the precipitation at 2400, 3046, 4300 and 4800 m above sea level is 788.4, 1884.3, 435.3, and 1980.7 mm (Xin et al., 2012). This evidence further verified that the changes of precipitation with increasing altitude were apparent, and showed that precipitation increased mainly at higher altitude areas. Furthermore, the study area was also an obstruction to the eastern Asia monsoon and a thoroughfare to the southern Asia monsoon (Li et al., 2012a,b; Zhu et al., 2013). Due to the influence of the eastern Asian and southern Asian monsoon, spatial change of precipitation extreme events also exhibited differences. The spatial distribution for precipitation extremes exhibited a declining trend from southwest to northeast over the study region, which may reflect the influence of the longitudinal range-gorge system in the HDMR. Therefore, it is necessary to emphasize ongoing monitoring of extreme precipitation events in this area. More detailed studies are still needed to fully understand the underlying mechanisms of the temporal-spatial changes in precipitation extremes over the HDMR.

5. Conclusions

For the temporal variation features in precipitation extremes, PRCPTOT, RX1day, R95, R99, NW, R10 mm, R20 mm, R25 mm, and SDII non-significantly increased at the rates of 5.05, 0.27,4.21 and 1.5 mm/decade, 0.03 mm/d/decade and 0.43, 0.15, 0.03 and 0.09 d/decade during the study period, respectively. A decreasing tendency was found for RX5day, CDD, and CWD, and the regional trends for these indices were 1.2°mm/decade, 0.56, and 0.12 d/decade, respectively. The spatial distribution for precipitation extremes exhibited a declining trend from southwest to northeast over the study region, which may reflect the influence of the longitudinal range-gorge system in the HDMR. There were negative correlations between elevation and the magnitude of the trends of CDD, R20 mm, R25 mm, SDII, RX1day, R95, and R99, indicating that extreme precipitation events occurred mainly at lower altitudes over the HDMR. However, the correlation between elevation and other precipitation indices showed an increasing trend along with altitude, especially for NW and CWD. Moreover, the extreme precipitation indexes had positive correlations with the annual total precipitation, and their correlation coefficients were statistically significant at the 1% significance level, except for CDD. The continuous wavelet transform analysis indicated significant periodic variations with periods of 2–4 year, 5-year and 10-year in the extreme precipitation, and there was a 2–4 year resonance cycle with SASMI and EASMI. The South/East Asian summer monsoon was an important influence on precipitation extremes in the HDMR from 1961 to 2012.

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